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Grasping Objects in Immersive Virtual Reality Environments: Challenges and Current Techniques

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***Abstract*—In real-life, grasping is one of the fundamental and effective forms of interaction when manipulating objects. This holds true in the physical and virtual world; however, unlike the physical world, virtual reality (VR) is grasped in a complex formulation that includes graphics, physics, and perception. In virtual reality, the user's immersion level depends on realistic haptic feedback and high-quality graphics, which are computationally demanding and hard to achieve in real-time. Current solutions fail to produce plausible visuals and haptic feedback when simulation grasping in VR with a variety of targeted object dynamics. In this paper, we review the existing techniques for grasping in VR and virtual environments and indicate the main challenges that grasping faces in the domains. We aim to explore and understand the complexity of hand-grasping objects with different dynamics and inspire various ideas to improve and come up with potential solutions suitable for virtual reality applications.**

***Index Terms*—Virtual Reality (VR), Grasping, Haptic, Robotics, Human computer interaction (HCI), Interaction techniques.**

I. Introduction

Over the past decades, with the advancement in virtual reality (VR) devices and Human-computer interaction (HCI) studies, the need for simulation of human behaviour with realistic interaction has become vital for many applications (see Fig. 1), such as industrial training, medical and surgical simulation, and rehabilitation [1]–[3]. High-fidelity graphics in such virtual environments have been used to provide users with a relatively immersive virtual experience [4]. However, obtaining a fully immersed experience requires realistic interaction with objects within the environment, where forces and masses of the objects can be felt during the interaction [5]. Haptic devices for both fingertips and/or the whole hand enable users to feel and manipulate the 3D objects and explore the virtual environment through a kinesthetic and cutaneous perception [6].

When the user interacts with an object, grasping is one of the main intuitive action behaviours. Although grasping behaviour is natural, human hands can grab a variety of objects with different shapes, weights, and frictions. Grasping in the virtual environment is a challenging task, as an ideal grasping action must take into account the geometry and dynamic characteristics of the virtual object [7]. Despite the recent achievements in grasping techniques in VR, which have led to the emergence of some technological devices such as glove-based devices [8] and controller-based devices [1], [9]. More technical methods need to be explored in order to ensure stable, controllable grasping in virtual reality.

The grasping techniques in VR differ broadly in complexity according to the virtual object's properties, such as mass, size, and materials. Moreover, the object's stiffness plays a significant role in making the interaction with the object complex to simulate [10]. Most existing techniques focus on reducing the complexity of the grasping targets by simulating rigid bodies or objects with relatively simple and similar properties [11]. However, unlike rigid bodies, deformable bodies have high dynamic force attributes when the fingertips make contact with them. Therefore, obtaining stable grasping of deformable bodies while achieving realistic visuals and haptic feedback in virtual reality remains an open problem. In this paper, we aim to review the existing methods for grasping from the perspectives of haptics and visuals, including the properties of the target objects. Further, to focus on the techniques of grasping in VR, we also generally introduce conventional grasping methods to compare the grasping methods in virtual environments. Through this paper, we hope to summarise the main existing challenges in grasping simulation and improve the quality of VR grasping, potentially creating a direction for a new research agenda.

II. VR techniques

Objects with different shapes, masses, spatial positions and frictions can be grasped easily by human hands, which does not require too much effort [12]. Moreover, The process of realistic grasping is based on the laws of physics [13], according to *Blaga et al.(2021)*, virtual objects are predominantly grasped with power, while real-world grasping is mainly based on precision [14]. However, to simulate the same behaviour in virtual reality, the virtual environment can not restrict the human hand motion according to physics laws like real environment [13], which may cause visual irrationality. To achieve realistic grasping in virtual reality, in recent decades, existing techniques have made great progress in visual feedback, which can render realistic objects [15], while some

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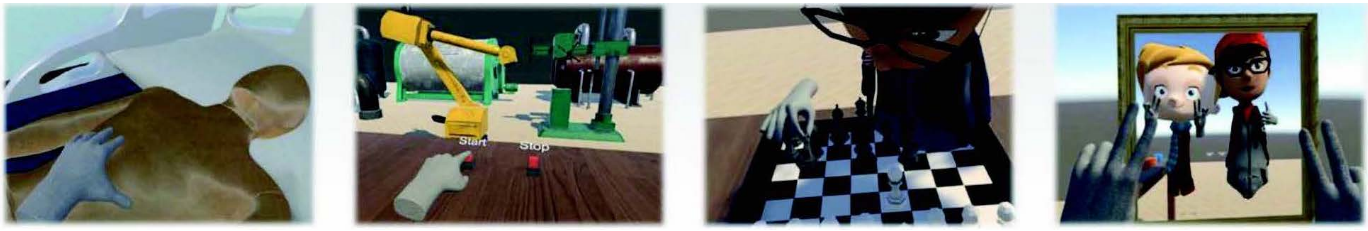

Fig 1. Realistic interaction with virtual objects within an immersed environment is crucial for many applications, such as industrial and medical training, entertainment and virtual social interaction [2].

types of technological devices have also been introduced to improve haptic feedback and rationalize interactions, such as haptic gloves, controllers, and haptic exoskeletons [16]–[18]. It is significant to understand the grasping mechanism, especially when it comes to tele-operations [19] and surgical operations [20]. In this section, we will discuss virtual grasping techniques which are centred around challenges and methods.

A. *Challenge*

Although grasping has made great progress in the development of current techniques, there are still challenges that remain in grasping simulation, especially in the simulation of precise grasping behaviour and grasping deformable bodies [11]. For large deformable bodies and heterogeneous deformation bodies [21], grasping becomes more challenging. Some designs of grasping deformable bodies approximate objects to rigid bodies [22], although this is limited. Most literature focuses on rigid bodies, as rigid bodies have relatively simple physical properties [23]. Further, the current VR technique has a high demand for grasping arbitrary targets with the improvement of the virtual environment. Hence, it is significant to define grasping challenges and find effective solutions.

1) High-Fidelity Modelling: High-fidelity modelling is an essential and basic step in virtual grasping. One of the important models is the human hand. The whole hand has 27 DoF(degrees of freedom), and each finger except the thumb has three bones, which are distal, middle, and proximal phalanges, also these fingers have three joints, which are MCP (Metacarpophalangeal), PIP (Proximal Interphalangeal), and DIP (Distal Interphalangeal) joints [24], [25]. Moreover, according to *Mulatto et al.*, the human skill of manipulating objects depends on the thumb's kinematics and on its capability of opposing the other fingers. The thumb has 5 Dof, which allows humans to perform spatial movements [26]. The complex features attract the attention of researchers. For a better simulation, *Burton et al.(2011)* introduce a kinematic model of the human hand regarding the precise mapping of thumb movements [26]. *Kuch et al.(1995)* also present a hand model which can use the analysis-based approach to research the hand motion [27]. Although we have been able to obtain relatively realistic models of human hands, it is hard to reproduce the surface stress based on the existing connection model between the human hand and the objects. How to model a precise and stable connection is still hard work [11]. Also, when it comes to free object manipulation, we need to consider the hand-bending range, one universal and effective way is collision detection. *Oprea et al.(2019)* introduced a visually realistic grasping system, which allows users to interact with or manipulate non-predefined objects based on collision detection [22]. However, this method has penetration problems, which decreases the quality of the interaction.

Additionally, most researchers use virtual rigid fingers to simulate the interaction between the hand and the objects, according to *Verschoor et al.(2018)*, using the soft fingers model would be an effective way to provide realistic feedback(see Fig 2, [7]). However, using a high-resolution soft fingers model is limited by the high computational cost and realism. Other approaches use a part of the deformable skin, which is considered as a soft pad with a rigid skeleton [28]–[30]. The proposed method by *Jacobs et al.(2011)* uses a new soft body model based on lattice shape matching (LSM) [28]. Although they increase the robustness of the object manipulations, the soft pad may collapse in some cases. Moreover, The compliance between the bones and the tracker interpenetration results will be another factor we need to consider. Existing soft finger modelling still faces many difficult problems to solve.

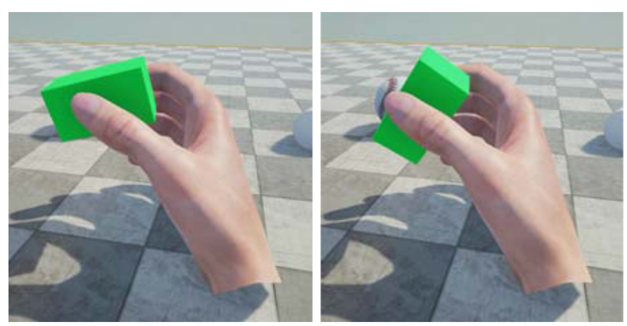

Fig 2. Soft hand simulations while interacting with virtual objects within virtual reality, where the proposed method does not support self-collisions of the hand nor support contact between deformable objects [7].

Visual Artifact and Overlapping: As mentioned before, current VR techniques do not allow the virtual environment to constrain the real hand motion like the real environment. It will lead to unrealistic grasp behaviour and visually distracting artefacts [13], like the penetration between the hand models and virtual objects. The results have a bad performance in

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visual feedback, although we could keep the virtual hand model outside of the objects (see Fig 4). In addition, Hand-object overlapping is always a common problem in computer animation. It does not only happen in 3D objects grasping but also in 2D objects grasping [31]. when the grasping targets have complex geometric features [32], like vases, stuffed toys, and some handicrafts, the interaction process will lead to penetration [33]. In some applications, due to cost reasons, the designers can not make detection in every frame, also, some video games more focus on bringing a fluent experience to users, which will ignore these computer animation problems. it is essential to find a low-cost method while avoiding penetration.

2) Device Performance: VR devices in recent years have been improved in humanization and intelligence, which is different from early VR systems [34]. The mainstream VR equipment includes visual HMD (Head-mounted display)and various types of haptic devices. Recently, The relatively famous visual display devices are HTC Vive series [35] and Oculus Quest series [36]. Just in the past year, Vision Pro owned by Apple could provide users with a deep immersive experience [37]. These devices have proved that MR (mixed-reality) can significantly improve users' immersive experience, which points the way for the development of virtual interaction. However, The considerations regarding the cost factor, process complexity, and safety factor become the obstacles which have blocked developers for many years. Especially the dexterity and portability of the device as well as battery life, which are problems that remain unsolved.

Moreover, other problems have also been exposed, such as the screen door effect (see Figure 5 [38]) and the barrel distortion (see Figure 3 [39]). The screen door effect is a well-known problem that bothers users in the virtual environment. It means a visible grid-like pattern of thin lines or gaps between pixels on the screen, similar to a screen door. The reason is the resolution of current VR displays is not high enough to match the visual acuity of the human eye [40]. According to *Nguyen et al.*, the solution of some commercial VR headsets is to use dispersive elements, which can effectively blur images on the screen [41]. On the other hand, Barrel distortion is particularly likely to occur in zooming a planar image using a spherical mirror, the image magnification decreases with distance from the optical axis [39], [40]. To solve this problem, reversing transformation should be one solution, however, it will highly complex lens design [42].

As we know, haptic devices have been widely developed by researchers, because the haptic can enhance the users' immersive experience [43]. Equipment with relatively complete haptic feedback includes some haptic feedback gloves [44], haptic feedback exoskeleton [45] and haptic devices like Touch Serious. These haptic devices tend to provide richer haptic feedback than controllers, which usually only provide force feedback. However, the devices either have difficulty delivering detailed renderings, are expensive to produce, or are not portable and wearable. Optimizing devices that can provide rich haptic feedback remains an important research direction.

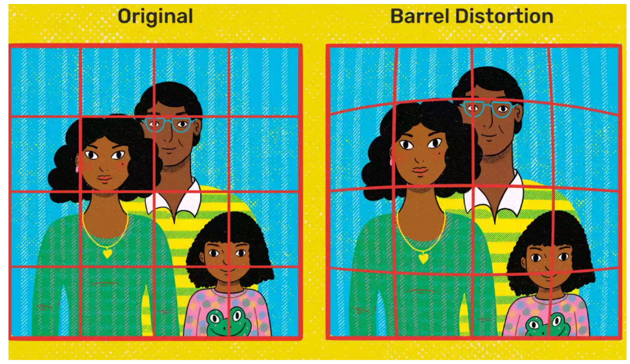

Fig 3. The comparison between original graphic and Lens distortion graphic [39].

3) Imperfect Theoretical Framework: A complete theoretical system has not yet been formed in VR grasping. In particular, there is currently a lack of a common metric. In robotic grasping, *Ferrari et al.* provide a well-known metric for grasp quality evaluation, which is Grasp Wrench Space(GWS). It refers to the set of all wrenches which can be applied to the object [46]. Through GWS, we can ensure the minimum distance between the origin and the boundary to explore the stability of the objects [47]. Moreover, within the robotic assembly research, The National Institute of Standards and Technology (NIST) presented a set of performance metrics and benchmarking tools, which contribute to technical specifications for robot systems [48]. This benchmark can also address deformable bodies, however, to our knowledge, we can not find a common metric or benchmark in VR grasping, especially for grasping deformable bodies. Hence, the theoretical framework for virtual grasping still needs to be improved.

B. Grasping Methods

1) Physics-based Methods: Generally speaking, grasping in VR should focus on achieving stable and realistic interaction in geometry. Most existing methods use physical input devices to achieve grasping behaviour, which is constrained by the laws of physics, called the physics-based method [49]–[51]. Specifically, when a 3D object model and a hand model are given, the VR system reacts to conscious action as a unique event by users touching off triggers or sensors, and then the target object can be grasped by a plan that generates hand object poses and hand joint angles to achieve stable grasp poses [52]. This method has been well-researched in robotics; it solves the problems related to force attributes, like resistance to slipping and force closure. Coming to deformable bodies, this kind of method could be used to explain the interaction between the elastic surface and virtual fingertips (see Fig 4). *Luo et al.* apply Bernoulli-Euler bending beam theory to the simulation of elastic shape deformation [53]. This non-linear model could handle compliant motions with friction and complex changes in contact areas, but it is still limited to contiguous areas. To solve this problem, *Tong et*

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*al.(2008)*introduce a non-linear contact force model and the beam-skeleton model for global shape deformation, which represent the multi-contact areas between the virtual hand and the deformable objects [54]. However, it depends on the performance of the devices. Although existing motion-tracking devices could sense the hand in a precise way, when the objects come to small, complex shapes or high-deformation, the precision will be limited.

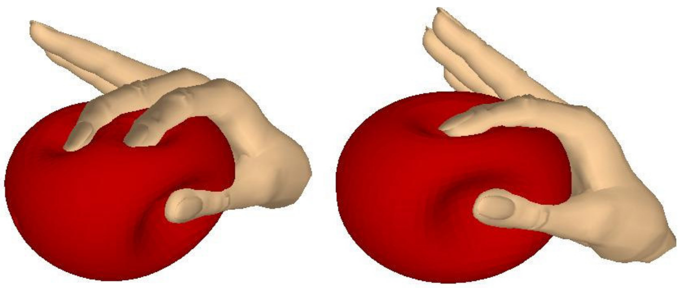

Fig 4. Illustrates contact force and deformation modelling for haptic simulation of grasping a deformable object with a realistic virtual human hand [54], which runs at an interactive rate and needs efficient methods to be able to run in real-time.

To address this issue and improve the quality of the grasping, the performance of the devices is to be enhanced. Recently, some designs aimed to synchronise the virtual hand and tracking hand, as it was difficult for previous devices to ensure that the tracking devices coordinated and matched, which would lead to visual disharmony [55]. The approach proposed by *Delrieu et al.* enhances the existing technique by coupling the virtual kinematic hand with the visual hand tracking system in order to achieve precision grasping [11], especially for small objects. In addition, providing hardware-based haptic feedback is also a good solution to optimise the users' experience [8]. *Jain et al.(2016)* introduce a VR system which could provide buoyancy, drag, and temperature changes [56]. *Liu et al.* use vibration motors to achieve the feedback on each finger [8]. *Choi et al.(2016)* introduce a wearable haptic device to provide binary force feedback, which is brake-based [57]. Although these devices do provide stable haptic feedback, as mentioned in the challenge, they always come with other drawbacks that cannot be ignored.

Force is the most significant physical constraint for haptic feedback, Simulating haptic feedback while grasping a 3D virtual object requires three-dimensional force/torque and a sufficient range of force magnitude to simulate contact forces during dexterous manipulation, and then render the power grasping of virtual objects [58]. Moreover, to simulate subtle changes of contact forces between fingers and objects, we need to consider the role of high force resolution and dynamic response. In some tasks that require accurate force feedback, such as rotating a virtual tumour in surgical simulation, the error of the feedback force should be less than the human discrimination threshold of force size [59]. Thus, the user can infer the tumour's stiffness via the interaction between the resistance force and movement [60]. In the simulation of the force, Most researchers also take friction into account [43], but not gravity. However, reproducing gravity is significant for improving users' haptic feedback experience to be able to feel the weight of the virtual objects. Not only in the virtual world but also in the real world, gravity has important physical meanings, and simulating gravity significantly improves the virtual experience. Although haptic devices can not simulate gravity in VR, users are made aware of the objects that are grasped successfully through vibration (or forces) feedback [61]. A possible way to generate gravity is to change the mass of the device, like changing the liquid mass in dynamic circulation to achieve the simulation of gravity of different levels [62]. Such methods need bulky facilities and face high-cost problems. Skin stretch has recently been researched and could be used to express texture, friction, slip, and force. It can display the tangential force on the finger surface, which simulates gravity. Based on skin stretch, *Choi et al.* designed a wearable haptic device that can simulate gravity to improve the grasping sensation [63].

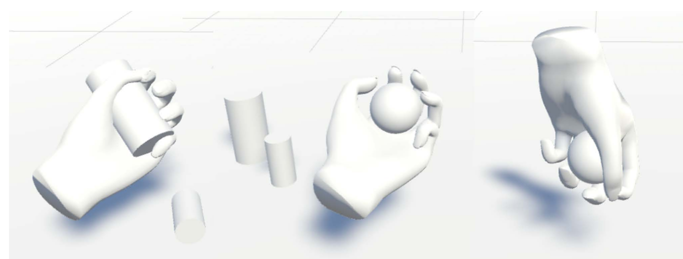

Fig 5. Shows grasping of handheld objects using geometric colliders, which employs GPU PhysX to detect collisions [64].

Collision Detection: Taking into account the collision between the object and the hand is another technique, which is called collision detection. Collision detection is the essential step of achieving realistic grasping, which refers to determining the intersection of two or more spatial targets. Although many existing gaming engines provide built-in collision detection algorithms, the complexity of the virtual environment in grasping sceneries requires stable and more efficient algorithms for VR. *wang et al.* proposed an improved collision detection method, which is based on mesh simplification and particle swarm optimisation [65]. this simplified method decreases the search space and improves the efficiency of collision detection. *Macklin et al.* present a method using particles to treat contact and collisions [66] and *Höll et al.* uses a simple ray-based technique according to a classic Coulomb contact model [67] but only for an unconstrained hand-object interaction (see Fig. 5).

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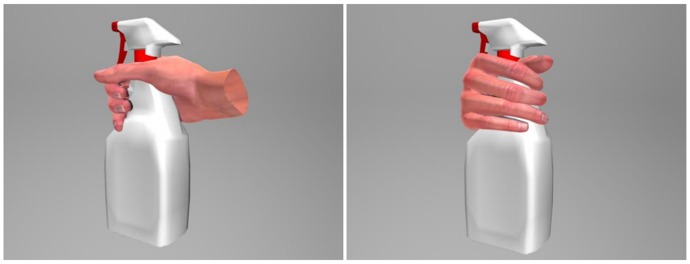

Fig 6. Shows grasping of a complex virtual object, where the virtual hand matches the object geometry based on pre-defined poses [68].

2) Other Visual Methods: example-based animation could be able to produce compelling visual results during the interaction, which can significantly improve the quality of the experience. However, such approaches are limited to objects which have a predefined animation [22]. It means we should have prior knowledge regarding the grasping objects, especially for the deformable bodies, the transformation rules need to be established [20]. In order to better achieve visual grasping, other strategies are like making the virtual object snap to the virtual hand [32], the design proposed by *Opera et al.* is a typical approach to snap the object to a virtual hand [22]. *Nasim et al.* introduce an interesting method to solve complicated tasks, once the virtual hand collides with the objects, the hand will be deactivated. the concept is similar to 'freezing' [69]. Although these approaches can achieve relatively stable grasping, the interaction result will be unnatural, which limits dexterous operations and users' experiences.

Motivated by the manipulation of the 3D models in computer animation, the deformation transfer has also been used in grasping deformable bodies. Deformation transfer refers to using mesh sequences to represent 3D models. Generally, deformation gradients over triangle mesh transfer the deformation information from the source model to the target model [70]–[72]. This method applies to 3D models which have complex shapes like toys or handicrafts (see Fig.6). The relatively mature and popular deformation space-defined method is cage-based. However, the method presented by *CHEN et al.* requires building the cage manually for different targets, which is not user-friendly for novice users [71]. *Le et al.* propose a cage-built method which could optimise the production of the initial cage [73]. This interactive cage generation approach saves manual effort. Another method also introduces a nested cage-based method, which sets hierarchies at a step-by-step level, it is especially applicable to complex geometry and topology [74]. Cage-based approaches have been used to optimize natural interactions in VR. Especially for deformable bodies, cage-based deformation control could express the deformation in logic. Additionally, compared with another conventional method–force control, cage-based has a lower computational cost.

3) Data-Driven Methods: Physically based simulations can preserve plausibility by simulating interaction forces. However, such physical models must be driven by a controller [75]. In recent years, other methods like Data-based methods also make remarkable progress. This method records how a human performs grasping and then synthesises grasp motions to gain grasping knowledge. The advantage is that synthesized grasp poses are consistent with real word data, which are natural-looking. Moreover, the grasping data can be collected by digital gloves and optical devices, and the direct way to construct a grasp database is to collect grasping data from human volunteers. This approach is time-consuming and cost-consuming for large-scale data acquisition. More and more researchers use data-driven methods to optimise grasping. *Goldfeder et al.* introduce a grasp database which contains hundreds of thousands of form closure grasps for thousands of 3D models [76]. *Zacharias et al.* present object-specific grasp maps to encapsulate an object's manipulation characteristics [77]. In addition, finding an appropriate grasp for an arbitrary object is a challenging problem, The grasping space needs to be considered with the DoF and geometry of the grasping targets, like *Pelossof et al.* use machine learning to select an optimal grasp from the grasping space [78].

Grasping rules were pre-defined for basic geometric primitives and could be used for other shapes. It works with databases which contain predefined poses, each one associated with an object geometry. Then, the most suitable grasp pose is selected according to the predefined grasp taxonomy or criteria. *Li et al.* introduce a shape-matching algorithm which matches hand shape to object shape by identifying collections of features, the matching is based on the similar relative placements and surface normals [79]. *Pollard et al.* describe an approach which combines human motion data and physics-based simulation [75]. This method synthesizes the grasping and manipulating motions by incorporating physical constraints, which could decrease the visual artefacts, especially for shape differences. *Tian et al.* present a real-time virtual grasping algorithm which computes the learned grasp space using machine learning and optimisation algorithms [80]. The learned grasp space is precomputed using support vector machines and represents a set of stable grasp configurations that can be used to generate plausible grasp movements.

However, such methods not only need plenty of time to build the dataset but also need to design excellent matching algorithms to save the time of traversing the dataset. Hence, improving the speed of indexing and matching is the direction in which the data-driven methods improve.

III. DISCUSSION

The purpose of virtual grasping is to simulate the real world and try to bring the users a realistic virtual experience, which prefers to present situations that do not exist or are not easy to exist in life. Unique virtual grasping strategies include animation-based methods, purely geometrical simulations and other visually plausible methods. *Kim et al.(2019)* and *Su et al.(2019)* have demonstrated the cage-based approach is capable of grasping objects in a complex environment [81], [82], where cage-based points can be used to deform object, although it does not apply to precise grasping. It can

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achieve stable force simulation, which is visually believable. Additionally, in recent years, some data-driven-based methods also through approximate matching to achieve stable grasping as well *Liu et al.(2019)* have already proposed that caging-based do have more positive performance in virtual grasping, compared with the conventional methods. They use collision geometry to find collision points, and then the virtual hand could hold the objects, although the grasp success rate will decrease when the targets come to complex bodies [8]. The difficulty of approximation remains unresolved.

In virtual reality, we use visual feedback to ensure stable grasping. Even haptic feedback is designed to optimise the rationality of the interaction in visual scenery, as there is no lightweight device that can reproduce rich haptic sensations. The current VR research direction focuses on improving the naturalness and rationality of the grasping in visuals. Therefore, optimising fluency, rationality, and fidelity in visuals will be the key to users' immersive experience. From this perspective, virtual grasping cannot sidestep the techniques of computer vision (CV), like the tracking technique. Tracking is a continuous estimation of the position and orientation of an object [83], which has achieved breakthroughs which can not be ignored. especially for hand tracking and hybrid tracking. Due to the high DOFs of the human hand and occlusion issues, hand tracking has been facing challenges. To address these problems, *sharp et al.(2015)* provide a flexible hand tracking system, which avoids the limitations of close distance and glove-assisted devices. This system is based on machine learning to generate a large dataset for hand-pose hypotheses [84]. Another classic technique is feature-based tracking, this approach usually extracts edges or corners, which could be used for calculating the distance. For some visual features which have difficulty recognizing humans, corresponding feature detectors offer a quick and reliable solution [83].

In recent decades, in addition to the classic methods mentioned above, some novel CV strategies have also been useful to the development of VR, such as cloud-based tracking technique [85], eye-tracking technique [86]. These technologies play an important role in enhancing human interaction with virtual objects. The development of VR is inseparable from the joint construction of multiple fields, breakthroughs such as recent advancements in the CV field can greatly promote the upgrade of VR interaction.

IV. Conclusion

In this paper, we reviewed the existing grasping techniques in the virtual environment. Grasping has been studied for over 20 years, however, the simulation of grasping in the virtual environment still faces some great challenges from the perspective of the visuals and haptics. As the future virtual environment becomes increasingly complex, how to guarantee the users' immersive experience and avoid lags in interaction have become the pressing problems of VR technology. Additionally, the solution regarding the challenges relies on the development of cross-disciplinary fields including materials, robotics, kinematics, computer vision and biology of the human behaviour. In this paper, we have identified the main issues with current techniques and potential areas for new research that are needed to address these problems. Moreover, in our future work, we are going to review grasping in the field of robotics and computer vision to get more of a map road for addressing the current limitations of grasping deformable objects in VR.

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